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Development of track component health indices using image-based railway track inspection data

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Ian Germoglio Barbosa, Arthur de O Lima, J. Riley Edwards and Marcus S Dersch

Abstract

The primary role of the US Department of Transportation (USDOT) Federal Railroad Administration (FRA) is ensuring the safe operation of railway rolling stock and infrastructure by way of regulatory oversight. FRA regulations require US railroads to conduct visual track inspections as often as twice per week depending on a specific track segment's FRA track class, which also governs maximum train operating speed. Such inspections are often subjective due to the inherent limitations of human visual inspection and cognition. Additionally, human visual inspections require some level of risk given the need for inspectors to be on track while also consuming valuable network capacity. As a result, and the desire to collect objective data to improve both safety and maintenance planning, railroads are pursuing new means and methods to assess track condition and evaluate track component health. This paper presents a numerical method to define track component health using field data collected on the High Tonnage Loop (HTL) at the Transportation Technology Center (TTC) in Pueblo, Colorado, USA. Line scan laser and image data of the track were captured using a 3D Laser Triangulation system and were subsequently processed using Deep Convolutional Neural Networks (DCNNs). The track heath quantification method proposed establishes benchmarks that were developed based on the understanding of railway track mechanics, high axle load (HAL) railroad engineering instructions, and FRA regulations. The novel metrics presented are referred to as Track Component Heath Indices (TCHIs) and are quantitative values that objectively assess track condition and provide a means to monitor condition change with time and tonnage. These data can be used in conjunction with traditional track geometry and other forms of track heath data (e.g. GPR and rail profile) to more holistically assess the condition of the track structure and its components and ultimately predict its future state.

Keywords

Track geometry, track infrastructure, track component health index, track inspection, track health, railway safety

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Introduction

In its role as a regulatory body, the United States (US) Department of Transportation (USDOT) Federal Railroad Administration (FRA) specifies track inspection intervals and the primary duties and qualifications of a certified track inspector.[1] Despite this guidance, and additional conservatism imposed by internal railroad operating procedures and business rules, the uncertainty and subjectivity of assessing the condition of track through human inspections is unavoidable. This need for increased objectivity has driven the railroad industry to pursue augmented human reality and artificial intelligence (AI) for certain track inspection tasks.

A variety of advances in rail engineering technologies have been developed and deployed over the past decade including Vehicle-Track Interaction (VTI) systems for track condition assessment,[2] Positive Train Control (PTC),[3] and non-destructive methods to determine rail component condition.[4–7] These, along with other new and emerging technologies, provide the rail industry with an opportunity to improve safety and optimize maintenance strategies to produce a network that is safer, more reliable, and more efficient. At the same time, there has been an upward trend in both rail traffic volumes and railcar axle loadings[8] which place increasing demand on the track infrastructure system and its components. With increased traffic and tonnage on most US mainlines, the rigor in which safety inspections are undertaken should increase commensurately. However, due to increased train traffic volumes and operating speeds, and more highly scheduled train

Rail Transportation and Engineering Center – RailTEC, Department of Civil and Environmental Engineering, Grainger College of Engineering, University of Illinois at Urbana Champaign, Urbana, IL, USA

Corresponding author:
Marcus S Dersch, Department of Civil and Environmental Engineering, University of Illinois at Urbana Champaign, 205 N. Mathews Ave, Urbana, IL 61801, USA.
Email: mdersch2@illinois.edu

operations stemming from Precision Scheduled Railroading (PSR), the availability of infrastructure for conducting traditional human vision-based condition assessment has decreased. To overcome increased utilization of assets and the desire to further reduce track caused derailments beyond the steady state condition of 0.85 derailments per million-train-miles over the past decade,[9] the rail industry must leverage new and embedded ways to gather data and observe track condition changes. From a financial perspective, delays caused by maintenance activities or service interruptions due to a lack of maintenance influence track availability for revenue generation through train movements. This, in turn, affects numerous stakeholders within the global supply chain including railroads, shippers, and the public,[10] reflecting the vital importance of proper management of track maintenance practices to minimize track maintenance disruptions and costs.

Improvements in rail transportation safety and derailment reduction have been an ongoing priority for both the rail industry and FRA, which is reflected in a 39% reduction in freight train derailments between 2005 and 2017.[11] However, with increasing demands on most primary rail corridors in the US, new technologies to help aid in inspection and maintenance have emerged, with growing utilization on Class I networks. The introduction of autonomous inspection systems leveraging three-dimensional (3D) laser-based triangulation and deep convolutional neural networks (DCNNs) can provide a solution to inventory, track, and optimize rail infrastructure assets.[12,13] When 3D laser technology is paired with properly trained DCNNs a variety of track components and conditions can be reliably detected.[13] The research described here within uses a 3D laser triangulation scanning system which combines pulsed, high-power, invisible laser line projectors and synchronized cameras to capture a high-resolution intensity image and range profile of rail track.[14] When track components are analyzed as a collective system, the output provides a holistic view of the track condition and gives insight to future problems the track may experience. Consequently, this gives researchers a wide range of analysis possibilities and data use cases, and targeted reports specific to different end-user's needs and job function can be generated.

The AI-based 3D laser technology requires a large amount of training data and proper validation to achieve high reliability and repeatability. As such, the High Tonnage Loop (HTL) at the Transportation Technology Center (TTC) in Pueblo, CO, USA was selected as a proof-of-concept test site starting in 2019. The HTL provided a rich test bed with many component varieties for training and the ability to collect repeated scans of data under rapid tonnage accumulation in a very short amount of time given the concurrent operation of the heavy axle load (HAL) test train as a part of the Facility for Accelerated Service Testing (FAST) operations. After multiple runs and training of the algorithm, 98% precision was achieved.[12,13] Additional information on the development of the DCNN and initial training data generated were described by Harrington et al.[13] Additionally, Harrington et al.[13] documented the development of a proposed methodology to report inspection data and established a benchmark for uniform representation of 3D laser scanning data using strip charts.

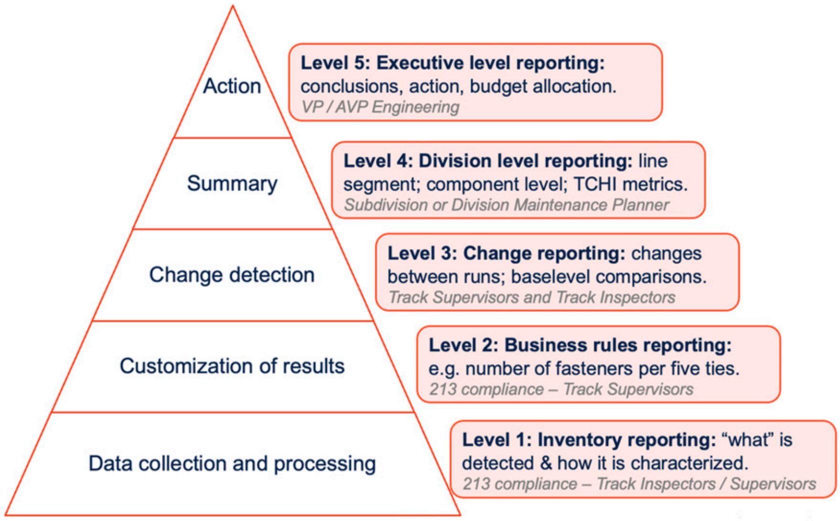
Methodology

Overview

Several manufacturers and technology service providers have produced autonomous machine vision systems that perform 3D laser scanning of the track superstructure and its components. The system used in this research was developed by Railmetrics, Inc. (a subsidiary of Pavemetrics, Inc.) and is known as the Laser Rail Inspection System (LR*AI*L). The LR*AI*L system is unique in that it has very high 3D scan resolution (i.e., more than 100 million points per second), with simultaneous capture of 2D images and broad AI-based inspection capability which can identify ballast level and surface fouling, crossties, tie plates, fasteners, insulators, anchors, joint bars, and rail wear. The LR*AI*L system is capable of inspecting track at typical mainline track speeds and data are typically collected at either one or two mm intervals. Data are then combined into range (laser) and intensity (line scan) images that are two meters in length. These images are subsequently evaluated by the DCNNs which identify various attributes related to the health of the track system and its components. The LR*AI*L system and its attributes were described in greater detail by Fox-Ivey et al.[12,14] and Harrington et al.[13]

The depth and breadth of the data collected by LR*AI*L present an opportunity to process and present information to a variety of end users within the railway organizational structure. Distinct end-users have disparate use cases for such data and need to consume it at a different level of specificity. The combination of different LR*AI*L outputs can generate insight for track inspectors, maintenance planners, and senior management. Figure 1 identifies proposed reporting levels and associated end-users at a high-level, as well as who would be the primary and secondary end-users for each analysis output, along with the major analysis that can be performed using LR*AI*L data.

Some of these outputs are: track/component change over time/tonnage; inventory, for asset management; real-time track changes, used for augmented reality during track inspections (for future development); track component health index, which are created using the methodology described in this paper; component rate of change, also known as degradation rates; subdivision track component health index (TCHI), which are a combination of the individual track component metrics; and the subdivision metrics over time, which analyze the subdivision TCHI over time and see how the degradation is behaving and how maintenance procedures are performing. Inventory charts, for example, are the most useful tool for tracking assets over time and providing a general overview of the railroad track structure and its components. The metrics developed as a part of this research are collectively referred to as the Track Component Health Index (TCHI), which will be further discussed in the following sections. They are generated by obtaining linear data using LR*AI*L, processing these data



LR*AI*L Output / Data Visualization Method	Pyramid Level (Figure 1)	Track Inspector	Track Supervisor	Maintenance Planner
Track Changes Over Time	Level 3	P	P	
Inventory Chart	Level 1		P	P
Real-time Track Change Visuals	Levels 2 and 3	P	S	
Track Component Health Index	Level 4		P	P
Component Rate of Change	Level 3	S	P	S
Subdivision TCHI Metrics	Level 4		S	P
Subdivision Metrics Over Time	Level 4		S	P

P = Primary User; S = Secondary User

Figure 1. Data analysis and utilization pyramid as well as example data outputs for example end-users.

using DCNNs, and then distilling these data into clusters and other metrics for visualization via bar charts, GIS-based maps, and strip charts.

Regulations for US track conditions are described in US Code of Federal Regulations (CFR), Title 49, Part 213 – Track Safety Standards.[15] CFR Part 213 is further interpreted and described in commentary form by way of the FRA Track and Rail and Infrastructure Integrity Compliance Manual,[16] hereafter referred to as the "Compliance Manual." In addition, railroads maintain their own, more restrictive, set of rules that are referred to as "engineering instructions"[16–18] to provide guidance to field personnel who construct and maintain track. Typically, engineering instructions contain information about track component selection, patterns, sizes, and quantities. This study leveraged the collective of these documents, along with relevant peer-reviewed literature and other documentation of research to create numerical and objective condition thresholds for each component. These rules and thresholds can be adapted to meet the needs of different end-users.

LR*AI*L data are processed using the trained DCNNs and results are output in a manner that classifies component location, presence or absence, and condition in Comma Separated Values (CSV) file format. The magnitude of available data varies based on the component type (and resulting density) that is inspected. Track component, track geometry, and crosstie-based information are reported in the output file, along with geographical information (i.e., GIS), and track stationing. At the base level (Level 1) of the pyramid (Figure 1) an inventory of components was generated based on the direct output of the DCNNs. Subsequently, business rules were applied for fasteners, ballast, and crossties as a part of Level 2 (Figure 1). Indices are calculated based on the number of components present or, in the case of ballast, the relative height to the top of the crosstie and range from zero (worst condition) and 10 (best condition). Next, individual component indices were combined and weights assigned to each of them. This process led to the development of a variety of Track Component Health Index (TCHI) values to provide an objective numerical evaluation of the track based on the current condition of its components. TCHI outputs can be reported and displayed graphically using histograms, bar charts, GIS maps, and strip charts, the latter of which is the predominant method for visualizing track geometry data. These visualization methods can be customized based on the function of employee consuming the data (e.g., track inspector vs. division maintenance planner) to maximize its utility for their respective roles and need for track condition information.

While the use of indices to objectively quantify track health in a continuous manner along the track is not new, the development and application of indices to assess track component health using imaged-based sensing data is novel. Examples of previous indices that have been developed to assess the track structure include the FRA Track Quality Index,[19] U.S. Track Roughness Index,[20] Swedish National Railway Q Index,[21] Chinese Track Quality Index,[22] Ballast Fouling Index,[23] and the Track Structural Index).[24] These indices - when they include the track superstructure – tend to overlook the assessment of components and are primarily focused on the presentation of track geometry data. This is reasonable given the maturity and prevenance of track geometry systems relative to the emerging inspection technologies that are vision and laser-based. Taken as a whole, existing and emerging indices can be used in tandem to accurately assess track condition, establish degradation rates, and improve safety and maintenance planning.

Default thresholds

Railway track components function as a system,[25,26] and each constituent component must be analyzed in order to develop composite indices related to track structural health. This section details the selection of the default compliance and safety thresholds for cut spikes, screw spikes, elastic fasteners, anchors, crossties, and the ballast section. These were selected based on multiple criteria, inspection distances, and documents, which will be detailed in each of the following subsections. Taken as a whole, the compliance thresholds (orange lines in later figures) are based on engineering instructions from Class I Railroads or compliance thresholds described in the FRA Track Safety Standards (CFR Part 213),[15] whereas the safety thresholds (red lines in later figures) come directly from CFR Part 213.[15]

Cut and screw spikes

Cut spikes are the most common rail fastener used on North American railroads.[27] Due to the variety of spiking patterns adopted by the railroads and the lack of research quantifying the influence of missing or broken spikes on track performance, determining maintenance and safety rules for spikes is challenging. Independent of the specific spiking pattern, it is generally expected that each tie plate will be installed with at least two spikes.[18] Thus, any condition of less than two spikes per plate is classified as exceeding the safety threshold. To develop business rules, inputs were obtained from an industry expert with experience in the use of cut and screw spikes at a Class I railroad. It was determined that 20% missing spikes would be used as a baseline maintenance threshold, which may be prioritized if additional indicators are also present, such as increased track gage.

The safety threshold for missing spikes should not be stricter than what is applied to broken crossties, presented at the subsequent subsection, as it is generally accepted critical to have one missing spike than one defective crosstie – which contains four or more spikes. However, raising the missing spike threshold beyond 40% (number used for crossties) does seem adequate for two reasons. First, there is no experimental data to inform such increase. Second, spikes may be present but may be ineffective (e.g. broken within crosstie) and thus cannot be detected in a visual or laser-based inspection.[28] Thus, given that it is incompatible with crossties to make the threshold lower and unsafe to make it higher, the authors selected 40% of missing spikes. Additionally, a moving inspection window of 25 crossties was selected for cut spikes. This roughly corresponds to the prevailing inspection distance of one rail length (40 feet)[1] considering typical timber crosstie spacing of (495 mm) 19.5 inches. This inspection window was also chosen to facilitate efficient calculations since the data are output on a crosstie-by-crosstie basis.

Elastic fasteners

Elastic fasteners apply a vertical clamping force (i.e., toe load) to restrain the rail from moving longitudinally relative to the crosstie.[29] They are used primarily with concrete crossties, and despite some relationship to cut spikes in their design function, installation method, number per crosstie, and interaction with other components is quite different.

The elastic fastener compliance threshold was generated using CFR Part 213, which states that "concrete crossties shall not be configured with less than two fasteners on the same rail".[15] Further, the threshold was evaluated in light of results from a field study on the effects of missing or broken fasteners on gage restraint of concrete crossties on Amtrak which showed that three consecutive crossties with missing clips were needed to significantly reduce gage restraint.[30]

Hence, a business rule threshold of 40% or more of crossties with at least one fastener missing was selected while the safety threshold was defined as 60% or more fasteners missing. Further, based on the ranges proposed by Maal and Carr[30] an inspection window of five crossties was chosen.

Anchors

Anchors are responsible for resisting longitudinal rail movement[31] and are mostly used in timber crosstie track. Consequently, this rule is only considered in areas of timber crossties. The compliance threshold was selected based on a Class I railroad's engineering instructions (which was representative of the industry) that stated that every other crosstie should be box anchored. Also, due to the nature of this rule, the inspection window varies based on how many consecutive crossties have missing anchors. Anchors missing on consecutive crossties may represent a larger issue, thus we increase the size of the inspection window if the data show consecutively missing anchors.

Crossties

The FRA compliance manual states that crossties are evaluated individually by the definitional and functional criteria set forth in its regulations.[16] Crosstie "effectiveness" is inherently subjective and requires judgment in the application and interpretation of the regulations.[16] Initially, a crosstie grading score is given by Railmetrics' internal data processing system that consumes LR*AI*L data. This value is obtained by evaluating the dimensions of splits and cracks on the surface of the crossties and assigning an overall crosstie grade. Railmetrics' algorithms first classify each crack according to its depth, width, and length into six different categories, and then by combining the results of all cracks in a single crosstie, an overall condition is determined based on the surface area (Table 1).

According to CFR Part 213.109 [15], each 39-foot (11.9 m) segment of track shall have a minimum number of crossties depending on the class of the track, geometry characteristics, and crosstie material (Table 2). Incorporating these parameters and requirements the safety limit for crossties was defined as 40% of failed crossties or 70% of near failure crossties in a 25-crosstie moving window. The compliance limit was defined as 25% of failed crossties or 50% of near-failed crossties on the same 25-crosstie moving window.

Ballast

The ballast is expected to transmit and distribute track loads to the subgrade, restrain track movement, and facilitate water drainage.[18,32,33] Given the dynamic rail loading environment, the ballast section changes over time due to weather, interaction with other components, and train loading. Abrupt changes in ballast profile can negatively affect track performance, thus monitoring its level and condition is critical.

Prior research relates lack of lateral resistance to insufficient ballast, fouled ballast, or a combination of these factors.[34,35] The LR*AI*L system is limited to analyzing what is visible from the surface, hence only ballast level is reported as the absolute distance between a plane drawn between the top of both rails and the mean height of the ballast surface (Figure 2). Results are reported on a one-m basis and separately for crib, left, and right shoulder.

The design ballast section and profile are defined by each Class I railroad and is typically dependent on crosstie type, track use (e.g., mainline, siding, industrial), and degree of curvature. According to one Class I railroad's engineering documents,[18] the ballast level should be level with the top of the crosstie. This requirement delineates the first compliance threshold for ballast when the height of ballast is below top-of-crosstie.

Lower and low ballast levels demonstrate a reduction of track structural capacity as demonstrated in results from various studies investigating different ballast levels and lateral resistance and their implication on safety.[34] However, it is known that other mechanisms command the structural behavior of the ballast section and due to the LR*AI*L's inherently limitation of visualizing only the surface, the research team had to decide what threshold would be considered as a safety limitation. Hence, a safety threshold was established as the point in which the ballast level reaches 50% of the crosstie height.

Business rules summary table

A summary of the business rules introduced in the previous sub-sections can be found in Table 3.

Results

Validation of results

For validation purposes, a subsection of the HTL at TTC referred to as Section 3 was used. This 2800-feet long section was chosen due to the quality and completeness of the data available. It was comprised of both concrete and timber crossties, which allowed researchers to validate the premises and calculations presented earlier in this paper. This was accomplished by first conducting a ground truth survey, visually checking the images and comparing findings to the results output by the DCNNs to data collected by human inspectors on the ground. Further

Table 1. Crosstie crack classification methodology with crosstie condition rating.

Classification	Depth	Width	Length
Very severe	Defects in crossties which contain ballast materials		
Severe	2 cm or greater	5 cm or greater	60 cm or greater
Moderate	1 to 2 cm	3 to 5 cm	15 to 60 cm
Light	Not considered	1 to 3 cm	10 to 15 cm
Very light	Not considered	0.5 to 1 cm	Not considered
Unmarked	Not considered	Under 0.5 cm	Not considered

Rating	Numerical value	Overall crosstie rating
Failed	3	More than 3.7% of crosstie surface containing very severe, severe, moderate, or light defects
Near failure	2	Between 3.7% and 3.1% of crosstie surface containing very severe, severe, moderate, or light defects
Fair condition	1	Between 3.1% and 2.6% of crosstie surface containing very severe, severe, moderate, or light defects
Good condition	0	Any crosstie which does not fall into the 3 above categories

Table 2. Minimum acceptable number of crossties in a 39-foot (11.9 m) track segment based on FRA track class.

	Numerical value		Overall crosstie rating	
FRA track class	19-In spacing	24-In spacing	19-In spacing	24-In spacing
Class 1	19 (79%)	14 (74%)	18 (75%)	13 (68%)
Class 2	16 (67%)	11 (58%)	15 (63%)	10 (53%)
Class 3	16 (67%)	11 (58%)	14 (58%)	9 (47%)
Classes 4 and 5	12 (50%)	7 (37%)	10 (42%)	5 (26%)

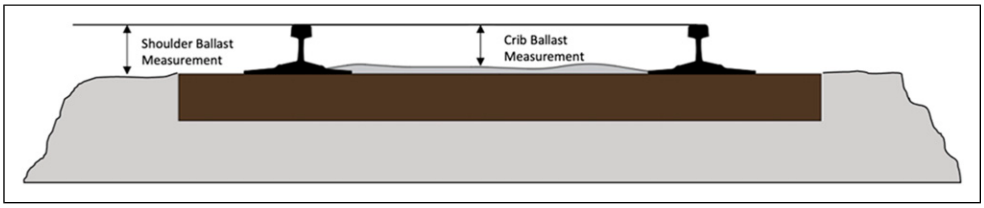


Figure 2. Ballast level measurement methodology.

Table 3. Summary of business rules developed by RailTEC.

Component	Criteria	Inspection window	Compliance rule	Safety rule
Cut and screw spikes	Presence	25 crossties	20% missing	40% missing
Elastic fasteners	Presence	5 crossties	40% missing	60% missing
Anchors	Presence	Variable	Flagged when different from every other tie anchored	
Crossties	Grading	25 crossties	25% failed ties or 50% near failure	40% failed ties or 70% near failure
Ballast	Crib and shoulder level	10 m	Less than top of crosstie surface	Less than 50% of crosstie height

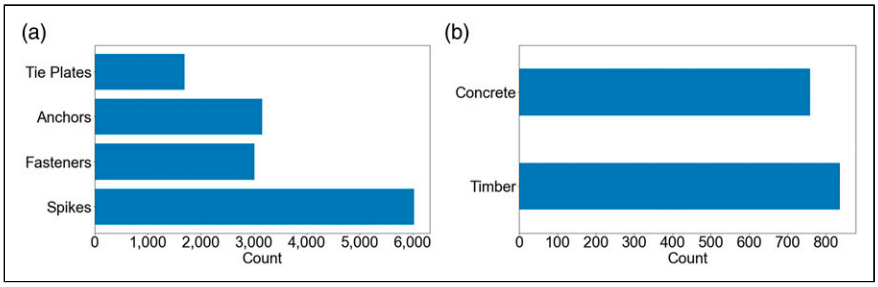


Figure 3. (a) Number and type of hold-down devices in Section 3 of HTL (b) and number and type of crossties in Section 3 of HTL.

discussion on data validation was documented by Harrington et al.[13]

Track component inventory

The first and lowest-level output (Figure 1, lowest level) is component inventory. This output provides a count of each component (e.g., crossties, fasteners, anchors, etc.) (Figure 3(a)) and also specifies the type of components (e.g., timber or concrete) (Figure 3(b)). This information is useful when assessing the status of the wholistic quantity of railroad infrastructure components, especially if the need arises to address a pervasive maintenance challenge that requires systematic replacement. Capital planning teams can use this information to forecast future expenses and management teams can use to see overall performance of track components and provide guidance on where more detailed track inspection may be needed.

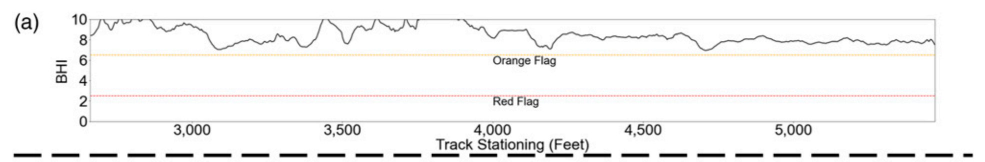
Track component health index

As mentioned, the authors created a new metric that combines linear data output from LR*AIL* and business rules and safety thresholds developed using the FRA Track Safety Standards[15] and internal Class I railroad engineering practices.[17,18,36] This novel metric takes advantage of the rail industry's familiarity with strip chart data to perform geometry data visualization as stated by Saadat et al.[37] to show health information about infrastructure components. First, component-level TCHIs for ballast, crossties, spikes, and e-clips are calculated independently. They are subsequently combined into a single Track Component Health Index (TCHI). The following sections provide detail on TCHI calculations using example data from the HTL at TTC.

Ballast health index

As described in the methodology section, ballast business rules are essential to quantifying track structure support and stability. To establish numerical index values for ballast height data and implement it to the BHI, the first step was to determine an equation that uses the ballast level as an independent variable. As the distance between top of rail and top of ballast increases (Figure 2), the BHI value decreases. To calculate the BHI, the height of the ballast at the crib and shoulder are compared to the top of the crosstie. Figure 4 shows the relationship between BHI and ballast height based on business rules and method of prediction as well as calculated BHI values for the HTL section under study.

The dashed lines represent the compliance (orange) and safety (red) thresholds of 6.5 and 2.5, respectively. A 10-m (33-foot) moving window was considered for all BHI calculations. Shoulder and crib ballast outputs were given equal weight when combined into a single metric, thereby lower values of BHI may be related to problems in the



Ballast Level (mm)	Ballast Health Index (BHI) Value	According to
205.00 or less	10	Estimation
209	8	Estimation
212.24	6.5	Compliance Threshold – Top of crosstie height
232.24	6	Estimation
256.69	5	Estimation
280	3.5	Estimation
301.14	2.5	Safety Threshold – Half of crosstie height
310.00 or greater	0	Estimation

Figure 4. (a) Ballast Health Index (BHI) results for 2,800-ft section under study and (b) ballast data points for calculations

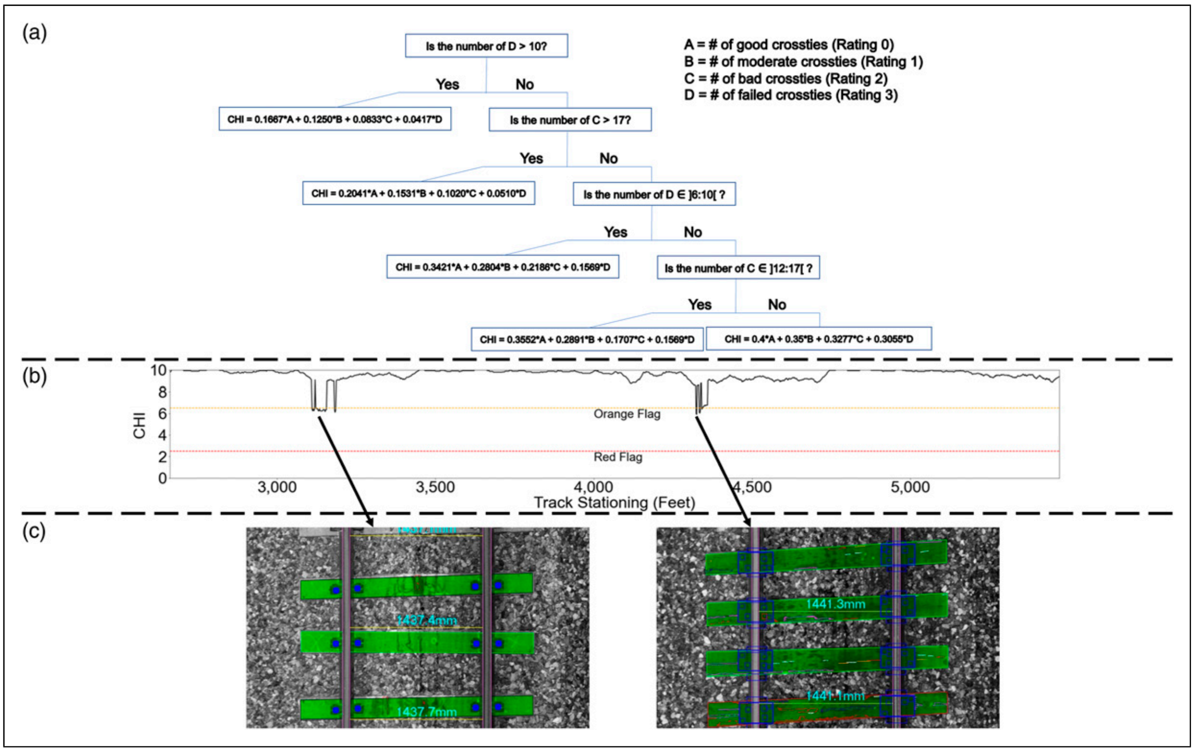


Figure 5. (a) Crosstie Health Index (CHI) calculation decision tree with equations, (b) results for 2800-ft track section under study with two areas with distinguishably lower CHI values, and (c) example concrete (left) and timber (right) cracked-crosstie images from CHI valley as indicated.

whole section (i.e., shoulder and crib ballast) or a single section of the ballast that is insufficient (i.e., low shoulder ballast).

Crosstie health index

The Crosstie Health Index (CHI) relies on the crosstie grading system explained earlier in the Default Rules section. The CHI uses a moving window of 25 crossties, which was selected based on the FRA required inspection window of 39-foot. The CHI identifies the combinations of good, moderate, bad, and failed crossties within the 25-crosstie moving window. The DCNNs evaluate and grade each crosstie from zero to three, representing good to failed crossties, respectively. The first step in the CHI calculation is to count the number of crossties in each rating category for every moving window in the dataset. Next, using a decision tree these values are input into different equations, created based on multiple combinations of the 25 crossties with different conditions. Like the BHI, compliance and safety thresholds were established for the CHI. The decision tree with equations, CHI output for the HTL section under study, and examples from two low-scoring sections are presented (Figure 5(c)) to provide confidence in the CHI methodology and results.

Fastener health index

The most complex index to calculate is the Fastener Health Index (FHI). This is due to the heterogeneity of fasteners,

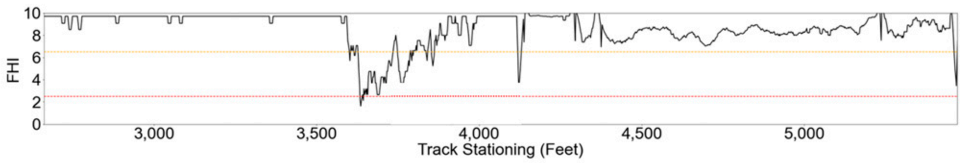
(a)

Number of Fasteners in a five-crosstie window	Fastener Health Index (FHI) Value	Obtained By
20	10	Estimation
19	9	Estimation
18	8	Estimation
12	6.5	Compliance Threshold – 40% missing fasteners
10	5	Estimation
8	2.5	Safety Threshold – 60% missing fasteners
2	1	Estimation
0	0	Estimation

(b)

Number of Spikes in 25-crossties window	Fastener Health Index Value	According to
200	10	Estimation
180	8	Estimation
160	6.5	Compliance Threshold – 20% missing fasteners
140	5	Estimation
120	2.5	Safety Threshold – 40% missing fasteners
75	1.5	Estimation
40	1	Estimation
20	0	Estimation

(c)



(d)

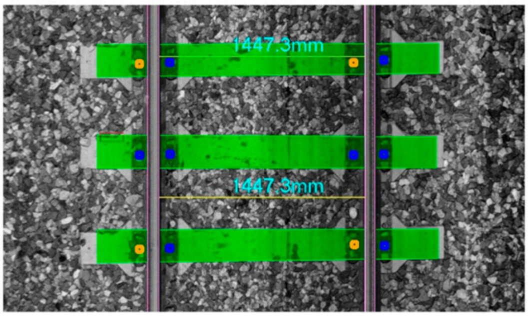


Figure 6. (a) Fastener health index (FHI) equation for concrete crossties with elastic fasteners (b) Fastener health index equation for timber crossties with cut spikes, (c) Fastener Health Index (FHI) for Example Track Section, and (d) example at Track Stationing 3800 indicating incorrect results due to untrained output.

variability in how business rules are applied across the various railroads, and other differences in fastener requirements based on crosstie type. For concrete crosstie track, elastic fastening system rules and calculations are used. For timber crosstie track, two different calculations are used: one for cut and screw spikes, and another for elastic fastener systems, which combine spikes and elastic fasteners. Business rules for concrete and timber crosstie track, FHI calculations for the HTL section under study, and an example of an incorrect evaluation are presented (Figure 6).

For concrete crosstie track, the FHI equation is based on the number of clips present in a five-crosstie moving window. Figure 6(a) presents the relationship between number of fasteners present and FHI in the window. These relationships were defined based on Class I business rules, research experience, and parameter estimation. For timber crosstie track sections (Figure 6(b)), the FHI for cut and screw spikes locations is based on the same methodology as concrete crosstie sections. That is, the FHI is based on the total number of expected spikes in the 25-crosstie window for timber sections. Finally, for timber crossties with elastic fastening systems, a combination of the two previous methodologies is used to generate the FHI. That is, the 25-crosstie window used for timber crossties is used to evaluate the spikes while the five-crosstie window used for concrete crossties is used to evaluate the elastic clips. Weights are applied to the two calculated values to determine the overall FHI for the section. Specifically, the elastic fastener is given a 60% weight (i.e., makes up 60% of the total FHI) and the spikes are given a 40% weight (i.e., make up 40% of the total FHI). For this study, transitions between crosstie materials were not evaluated due to the inherent challenges associated with boundary conditions, though rules could be developed for them in the future.

An example FHI output for the HTL section under study indicates that the fasteners were mostly above the yellow

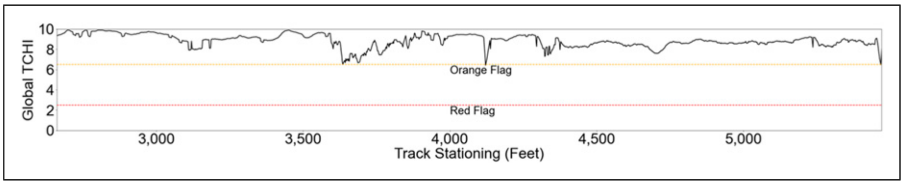


Figure 7. Track component health index (TCHI) results.

threshold, with a subset of locations (e.g., near 3600 and 4150) indicating reduced health. Further investigation of the results between 3600 and 3900 indicated the presence of unique "dog-bone" crosstie with a complex and non-uniform pattern of fasteners the DCNN was not trained to recognize. While the fastening systems were correctly installed their condition was incorrectly identified as missing (false negative) due to the abnormal size of a rail seat (Figure 6(d)).

Track component health index

Following the calculation of each of the constituent component indices, a global Track Component Health Index (TCHI) can be generated for higher level evaluation of track health. The TCHI provides a holistic view of the health of the track infrastructure based on three track components previously analyzed (i.e., ballast, crossties, and fasteners). The combination of the different sub-indexes into the TCHI can be adjusted based on the specific needs and business rules of the end-user. For this study, and based on their critical function in providing proper track gauge, a greater importance was given to the fastener components (40%) while the BHI and the CHI were each responsible for 30% of the TCHI. Using equation (1) and the individual component indices as inputs, TCHI results were calculated for the 2800-foot section under study (Figure 7). Due the distribution of weights, the TCHI is most influenced by fastener condition (FHI) and has the lowest values at the same locations as the FHI. Nonetheless, around track stationing 3,200, we see a local minimum due to the combined influence of ballast level (BHI) and crosstie condition (CHI).

$$TCHI = 0.4\,FHI + 0.3\,BHI + 0.3\,CHI \qquad (1)$$

Conclusion

A system of track component health index was developed for the assessment of track health based on data output from the LR*AI*L laser-based track inspection technology. The methodology was intentionally developed to be technology-agnostic given the rapid development and deployment of sensing devices for the railroad industry. Thus, the methodology can be used with data from other inspection systems that output similar track component conditions.

Specific component indexes were developed and demonstrated for ballast (BHI), crossties (CHI), and fasteners (FHI) which were later combined and weighted into a global Track Component Health Index (TCHI). The TCHI methodology provides an analytical and numerical way to assess track component health and holistically understand rail superstructure condition. This method can augment the functions of different stakeholders in the railway industry and serve as an effective tool to monitor and compare the state of the track as it changes over time.

Results demonstrate that machine vision-based track inspections that generate linear track health and condition data can be a valuable resource for infrastructure owners. These data can be leveraged for the detection and tracking of condition change as a function of time and tonnage. The visualization of the data as demonstrated in this study can aid decision-makers in their prioritization and optimization of maintenance strategies to further mitigate of risk of track caused derailments. With recurring gathering, storage, and dissemination of these data, additional analytics may be developed for predictive maintenance and capital planning forecasting.

Further refinement of TCHI and its sub-indices presented here can be achieved by employing owner-specific business rules or engineering requirements resulting in more reliable and accurate assessment of infrastructure. Lastly, the nature of the LR*AI*L and the DCNNs employed allows the system to identify new components and be retrained when new data are collected, further improving system accuracy and precision.

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ORCID iDs

Ian Germoglio Barbosa https://orcid.org/0009-0006-8785-2055
Arthur de O Lima https://orcid.org/0000-0002-9642-2931
J. Riley Edwards https://orcid.org/0000-0001-7112-0956
Marcus S Dersch https://orcid.org/0000-0001-9262-3480

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